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6. AUTHOR(S)

Nader Engheta (PI)
Edward N. Pugh, Jr. (Co-PI)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Pennsylvania
Department of Electrical and Systems Eng
200 South 33rd Street
Philadelphia, PA 19104

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Polarization is an important feature of electromagnetic waves, and it can provide useful information about the observed scene and objects Without appropriate instruments human eyes cannot effectively sense the polarization of light. However, it is well known that eyes of certain animal species are sensitive to light's polarization. In this project, we explore the possibility of utilizing coherent motion of tiny dots superimposed on an image as means of representing and displaying polarization information on the image, while maintaining other features of conventional images. Our results show that image segments possessing coherently moving dots "pop out" in contrast with the rest of the image with randomly moving dots, and have demonstrated that coherent motion can be exploited in providing visual cues for polarization contents. The direction of motion of the dots in each segment of the image can be related to the preferred axis of polarization in that segment, and the degree of coherence can be used for representing the degree of linear polarization. In this report, first a brief background on the polarization vision will be given, and then our efforts on mapping polarization information onto visual cues using coherently moving dots will be presented.

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601 N. Randolph Street
Arlington, VA 22203-1977

By

PI: Nader Engheta (ESE Dept.)
Co-PI: Edward N. Pugh, Jr. (Ophth. Dept.)
Department of Electrical and Systems Engineering/Department of Ophthalmology
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Biologically Motivated Representational Schemes for Mapping Polarization Information into Visual Information

Abstract

Polarization is an important feature of electromagnetic waves, and it can be affected by surface shapes, materials, local curvature and features, and relative location of sources and objects, and thus it can provide useful information about the observed scene and objects Without appropriate instruments human eyes cannot effectively sense the polarization of light. However, it is well known that eyes of certain animal species are sensitive to light's polarization. In addition to the well-known navigational advantage of polarization sensitivity, it has been hypothesized that some species may have evolved polarization sensitivity as a mechanism of enhancing the contrast of targets in media that scatter light (e.g., under water).

Motivated and inspired by hypotheses about utility and nature of the polarization sensitivity of visual systems of certain species, we have been studying and developing imaging methodologies based on the "polarization-difference" signals. In our previous work, we showed that polarization-differencing greatly facilitated the detection of targets in scattering media, even when the targets produced only very weak polarization. We also developed some bio-inspired representational schemes for mapping polarization information into visual information, suitable for human observers and consistent with human visual system and perception.

In this project, we explore the possibility of utilizing coherent motion of tiny dots superimposed on an image as means of representing and displaying polarization information on the image, while maintaining other features of conventional images. Our results show that image segments possessing coherently moving dots "pop out" in contrast with the rest of the image with randomly moving dots, and have demonstrated that coherent motion can be exploited in providing visual cues for polarization contents. The direction of motion of the dots in each segment of the image can be related to the preferred axis of polarization in that segment, and the degree of coherence can be used for representing the degree of linear polarization. In this report, first a brief background on the polarization vision will be given, and then our efforts on mapping polarization information onto visual cues using coherently moving dots will be presented.

dots, however, add texture, so dot patterns should be designed to take advantage of texture.

Biologically Motivated Representational Schemes for Mapping Polarization Information into Visual Information

Background and Motivation

It is well known that wave-based navigation, direction finding, and imaging and detection of objects in scattering media present a challenging set of problems. The scattering of electromagnetic waves in media surrounding an object is a serious impediment to the proper function of imaging, detection, and navigational systems [1-4]. In the visual and infrared domains scattering due to suspended particulates in water and air in the form of fog, rain and smoke can seriously reduce target visibility [5], due to the reduction of target contrast at the imaging system by light scattered from the particles. Introducing novel ideas to reduce such fundamental limitations will open doors to new methods for imaging, information gathering, and detection and navigation when scattering particles impair system performance as in underwater environments and in fog and rain. Most imaging systems simply map total intensity spatially, sometimes with a few spectral channels, and are not efficient at seeing through scattering media, since scattered light degrades image contrast. Novel insight into methods for seeing targets in scattering media, and improving the quality of their images gathered in such environments, has come from examining the biology of visual systems of animal species thought to have evolved an ability to see in the presence of scatterers.

The underwater environment is a good example of a domain in which scatterers are present and limit the performance of imaging systems. Therefore, it has been a suitable place to look for a naturally occurring visual system that may have adaptations for improving the quality of vision in scattering media, and to attempt to introduce interdisciplinary ideas to overcome the limitations and constraints in imaging in scattering media.

Biological visual systems have developed coding strategies that enhance contrast in scattering media [6-8]. One well-documented strategy is the widespread use of long-wavelength light, as its lower scattering preserves image contrast over greater distances [8-9]. Biological visual systems in many species have also developed schemes to sense and utilize the light's polarization [10-17]. Polarization vision is an active field that investigates the biophysical mechanisms and functional roles of polarization sensing by biological visual systems [10-16]. Polarization itself is a fundamental characteristic of electromagnetic radiation, and plays an important role in the interaction of light with matter [5].

Human vision is "polar blind," and cannot effectively utilize the polarization of light even though polarization carries important information about the surface properties of objects and other aspects of the environment. Indeed, in our previous work we have shown that "biologically inspired polarization-differencing" can extend the distance over which objects can be reliably detected in scattering media up to 3-fold, even under conditions when the fractional polarization reaching the detector is less than 1% [18-20]. Extending the distance for detection and classification of objects near the limit of

visibility increases the time for critical, survival-relevant decisions, and is thus a major advantage in many real-time applications.

Polarization information has been used by researchers in several remote sensing applications ranging from machine vision [29] to biomedical imaging [30-31] to infrared target detection. In addition to its ability to provide previously unavailable information about scenes, polarization-difference imaging (PDI) improves target detectability in scattering media [18-20]. In our previous effort, we investigated the relationship between *polarization-sum*[1] (PS) and *polarization-difference* (PD)[1] information to determine if the two types of information could be combined into a single image to further enhance target identification [20]. Using the principal components analysis of polarimetric information, fundamental orthogonalities were discovered between the PS and PD processing channels [32-33]. Use of this information coupled with knowledge of the biology of human color vision [34] led to the development of novel display strategies for 2-channel colorimetric PD images [20]. Further development of the theory led to a fundamental understanding of the 3-channel-polarization-to-3-channel-color mapping first proposed by Bernard and Wehner [35].

Figure 1 shows one of the earlier images in our previous effort of an aluminum disk immersed in a tank of water to which small amount of milk is added, obtained using a conventional (i.e., PS) imaging (left panel), the PD imaging (middle panel) and the colorimetric PDI technique (right panel) [20]. In this example, the PS image provides us with the information about the boundary of the disk but not about the patches over this disk. The PD image, on the other hand, clearly shows the patches, but not the target boundary. The colorimetric representation of the PD image combines *all* the information into a single image using our novel 2-channel polarization mapping strategy. By combining PS and PD information, both the disk (visible in the PS image) and the patches (visible in the PD image) are readily observed in a single scene. The enhancement by the colorimetric PDI mapping of the visibility of the weakly (and orthogonally) polarizing square patches on the disk in the image is striking to the normal human observer.

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[1]A "polarization-sum" (PS) image is created from summing, pixel by pixel, the light gathered (successively) through two orthogonal linear polarizers. So $_{PS}I(x,y) = I_{\parallel}(x,y) + I_{\perp}(x,y)$. The pixel-by-pixel image is directly proportional to that which would be obtained by a conventional, polarization-insensitive imaging system. A "polarization-difference" (PD) image is, however, formed by subtracting, pixel by pixel, the light gathered through the two orthogonal polarizers, so one gets $_{PD}I(x,y) = I_{\parallel}(x,y) - I_{\perp}(x,y)$.

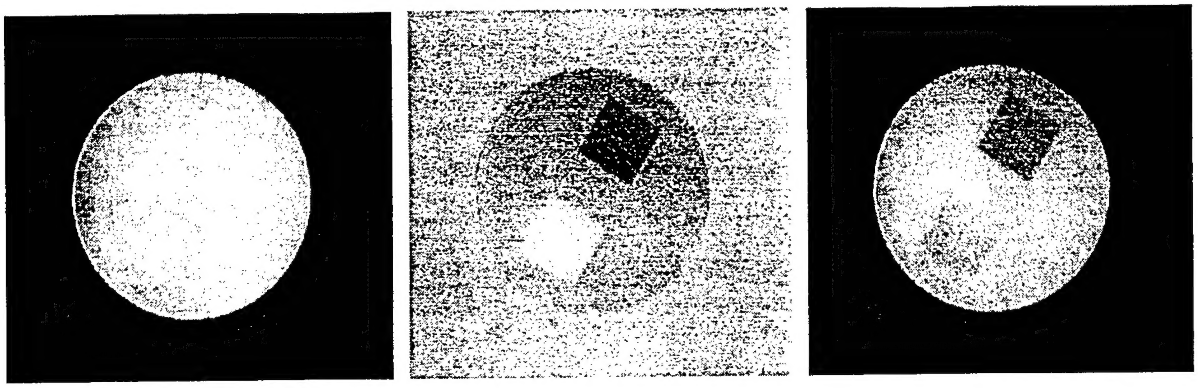

Fig. 1. A sample of our previous results obtained in our earlier effort. This is an example of the advantage of biologically inspired polarization-difference imaging. Left panel shows a conventional (i.e., polarization-sum PS image) of a prepared aluminum disk immersed in a tank of water with small amount of milk added. Middle panel shows the polarization-difference (PD) image of the same target under the same experimental condition. Right panel shows a colorimetric PDI image combining the information obtained from the PS and PD images. The square patches on the disk, which produce less than 2% net linear polarization in the image, are clearly detectable and discriminable in the colorimetric and PD images, but barely detectable and not discriminable in the conventional image.

How Can We Map Polarization Information into Visual Information/Cue?

It is known that polarization imaging contains useful information about surface shape, local curvature and features, and the relative location of light sources in the environment with respect to the object. However, in mapping polarization data into visual displays, it is important to note that since human eyes are polar blind, and yet that the outputs of any imaging and detection machines will eventually be viewed by human observers, the outputs of any polarization imagery, detection and navigation system should be exhibited in a way that will be easily perceived by the human visual system. Thus, the information from polarization-based imaging systems needs to be rendered or mapped to the display in a manner compatible with the biology of human vision.

Some of the known visual cues include:

(1) Intensity/Brightness
(2) Color
(3) Coherent motion (Shape/form from Motion)
(4) Textures
(5) Three-Dimensional visualization (shape from shading)
(6) Second-order motion
(7) Other cues

Previously we had shown that polarization-difference imaging (PDI) information can be usefully color-coded (the item (2) of the visual cues mentioned above) based on the opponent-colors model of the human visual system [20]. In such mapping, the polarization-sum (PS) signal and the magnitude of polarization-difference (PD) signal were represented by the colorimetric parameters brightness (B) and saturation (S), respectively, while the sign of PD signal corresponded to a pair of opponents hues (H and H+180°). The choice for the specific value of hue (H) presents a degree of freedom, which could be determined according to any suitable parameter. In our previous work,

we had selected the hue (H) based on the value of the polarization analyzer angle. This technique, which appeared to be simpler than some other polarization representational systems (e.g., [35]) and to be more suitable for observations made in scattering media, led to promising and important design features for contrast enhancement in imaging of objects in scattering media. Exciting results for such representational schemes were obtained that are easily understandable and naturally interpretable by human observers. (See e.g., Fig. 1).

Mapping polarization information onto intensity/brightness can be done by displaying polarization-sum (PS) signal and the magnitude of polarization-difference (PD) signal into separate black&white images. This was done, for example, in the left and middle panels of Fig. 1.

The work proposed under this grant was focused on mapping polarization information onto coherent motion, i.e., item (3).

Mapping Polarization Information into Coherently Moving Dots

Human visual system can detect and perceive coherent motion, moving objects, and form from motion easily and pre-attentively. Biological motion is easily perceived when signal dots are placed in a field of randomly moving noise dots [36]. Whereas perception of biological motion suffers under dim-light conditions, detection of coherent motion seems unperturbed so long as dot size and density are sufficient to support spatial resolution of the motion tokens [37].

The idea of mapping polarization information onto coherently moving dots can be described as follows: In a scene where there are many dots randomly located, it is known that coherently moving dots can be easily and pre-attentively distinguished from randomly moving dots. Figure 2 shows a collection of white dots on a black background. These dots are randomly located. A section of this collection contains dots that will move coherently in a particular direction, while the other dots either move randomly or they do not move at all. Human eyes can easily distinguish the section of coherently moving dots against the background of randomly moving dots (or non-moving dots). (Please double click on Figs 2 and 3 to see the movie clips of moving dots.)

Since the regions of coherently moving dots can be detected by the human eye, we explore the possibility of using such a visual cue as a means to display polarization information in an image. We can add/overlay small dots on an image. The size and number of these dots are chosen such that only a little or no change to the content of the original image is done. The regions of image, which contain some polarization, can be the ones with coherently moving dots, whereas the regions with no polarization can include dots that will be moving randomly. The direction of movement can relate to the direction of polarization of the corresponding region. So regions with dots moving in different directions represent regions with different polarization. (See Fig. 4) The

regions of interest may be the ones with randomly moving dots, while the other section of the image may have dots that are not moving. (See Fig. 5).

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Fig. 2. Collection of randomly located dots. A section of this collection includes dots that will move coherently, while the other dots will be moving randomly. Double click on the Figure to see the movie clip.

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Fig. 3. Similar to Fig.2, except the dots outside the section of coherently moving dots will stay motionless. Double click on the Figure to see the movie clip.

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Fig. 4. Similar to Fig.2, except the dots in the two regions of coherently moving dots are moving in different directions. Double click on the Figure to see the movie clip.

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Fig. 5. Similar to Fig.2, except the two regions of interest have dots that are moving randomly. The rest of the image contains dots that are not moving. Double click on the Figure to see the movie clip.

Brightness intensity of the dots is chosen such that the dots can be easily observed against the image. Here we can use two different ways of choosing brightness intensity of the dots. The first one is the "maximum contrast scheme", where brightness intensity is selected complement to the intensity of the corresponding nearby pixels of the original image. The second scheme is the "intensity modulation scheme". In this case the brightness intensity of the dot is chosen according to the local intensity of the image using the following relation,

$$I_{dot} = I_{image}\left(1 - M/100\right)$$

where I_{dot} and I_{image} are the brightness intensity of dot and the local image pixels, respectively, and M is the given percentage rate of intensity modulation.

To explore and test this idea, an original algorithm has been developed in the MATLAB environment. The results are presented as movie in *.mpg format. (These movie files can be viewed by Microsoft Media Player.

As an illustration of this technique, we use our target, which is an aluminum disk with two square patches on its surface. This is a 3.8-cm-diameter aluminum disk whose surface has been sandblasted to make it Lambertian, except for two 1-cm^2 square patches, which are not sandblasted, but instead they are "sand-papered" in two orthogonal directions, resulting in small polarization signatures.

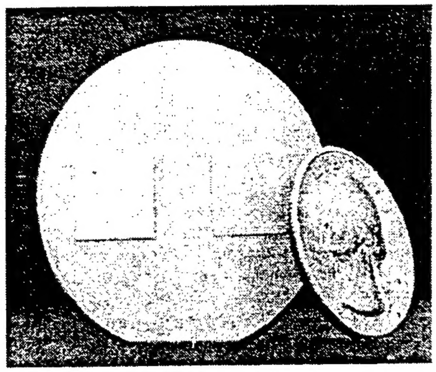

Fig. 6. One of the targets under test

Now we present images of this target with moving dots inserted to display the polarization information. Figures 7 and 8 present the mapping of polarization information of this image onto the coherently moving dots with two different directions of motion. In Fig. 7, the region with no polarization information is represented by randomly moving dots, whereas in Fig. 8 such a region contains dots that are not moving. In these two Figures, the brightness intensity of dots is chosen according to the "maximum contrast scheme". Figures 9 and 10 show similar images, but for the "intensity modulation scheme" with 30% modulation. Figures 11 and 12 present the images of this target, but here the dots in the polarization regions are being "stretched", instead of being moved. The direction of the "stretching" can map and relate to the direction of polarization. Such "stretching" of dots, and the regions in which these dots are located, can be easily detected by human eyes.

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Fig. 7. Image of the target disk, with coherently moving dots indicating regions with polarization information. The dots in these two regions are moving in orthogonal directions, mapping two orthogonal directions of polarization. Double click the Figure to see the movie. Here "maximum contrast scheme" is used for brightness intensity of dots.

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Fig. 8. Similar to Fig. 7, except the dots in the region with no polarization information do not move. Double click on the Figure to see the movie

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Fig. 9. Similar to Fig. 7, except here the "intensity modulation scheme" is used to assign the brightness intensity for dots. Double click on the Figure to see the movie

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Fig. 10. Similar to Fig. 9, except the dots in the region with no polarization information do not move. Double click on the Figure to see the movie

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Fig. 11. Similar to Fig. 7, except here the dots in the polarized regions are being "stretched", instead of being moved. Double click on the Figure to see the movie.

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Fig. 12. Similar to Fig. 11, but here the "intensity modulation scheme" is used for the brightness intensity of dots. Double click on the Figure to see the movie.

It is important to note that the "maximum contrast scheme" for the dot intensity works better when image intensity is more uniform, whereas the "intensity modulation scheme" is more preferable for the situations where certain parts of the image represent unimportant background whose intensity is close to zero. In these cases, this scheme enables one to concentrate attention on the region of interest, instead of background.

Using Textures for Mapping Polarization Information into Visual Information

We have also explored the possibility of using black-and-white (BW) textures to display and map polarization data. Figures 13 shows the use of textures (both static and dynamic textures) in displaying regions with orthogonal polarization information. The textures are formed by 25%, 10% and 5% intensity modulation in the region with polarization information. As can be seen from these Figures, the textured areas, which represent the areas with orthogonal polarization axes, can be easily detected by the human eyes.

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Error! Not a valid link.(C)

Fig. 13. Use of textures to show polarization information in our target disk. The percentage of modulation for these textures are 25% in A, 10% in B, and 5% in C. Double click on the Figures to see the movies for "dynamic" texture mapping of polarization.

We have also begun making a Graphical-User-Interface (GUI) panel to include some of the mapping strategies and representational schemes we have developed in this program (and the other mapping schemes we continue to develop in our current grant), in order to make the selection of a specific mapping technique easier. Figure 14 shows a sketch of this GUI. As can be seen, in this GUI panel we can choose various parameters such as dot movement directions, dot size, etc.

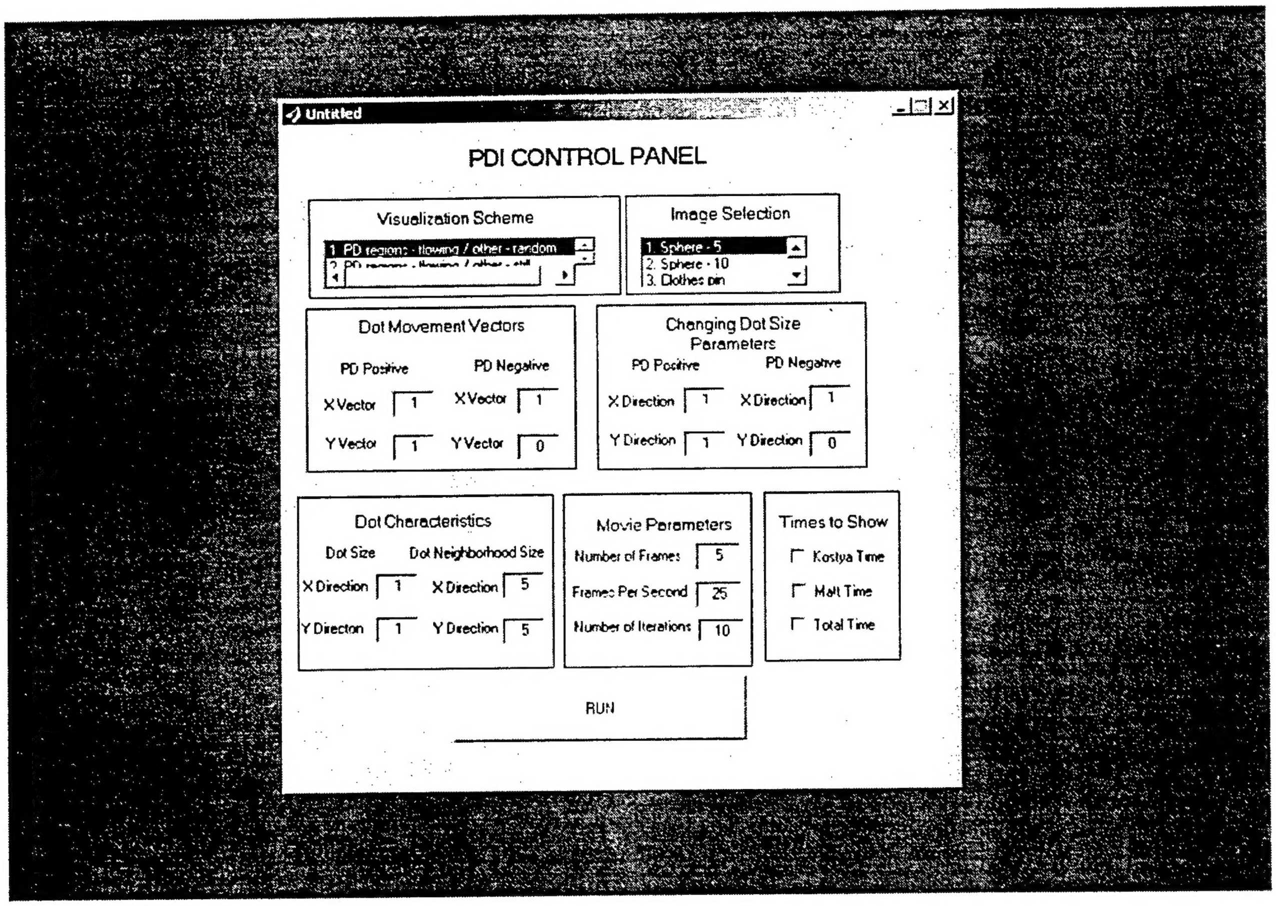

Fig. 14 Preliminary version of a GUI panel to control the characteristics of some representational strategies for polarization mapping.

Summary

In this project, we explored and developed certain representational schemes for mapping polarization information into visual information. In particular, in this effort we focused on mapping polarization information into coherent motion and into static and dynamic textures as some of visual cues suitable for such mapping. Our results have shown that

these visual cues can be interesting and exciting tools in representing polarization information.

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